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Energy use efficiency and greenhouse gas emissions of farming systems in north Iran

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ABSTRACT

Efficient use of energy resources in crop production is an important goal in sustainable agriculture. This study compares the energy flow in farming systems across farm size with their corresponding greenhouse gas (GHG) emissions - presented in terms of carbon dioxide equivalent (CO_2 eq.) - in the north of Iran. To reach this aim, primary data were collected by survey with farmers whose main activity was major crops production in the region that included wheat, barley, canola, soybean, paddy and corn silage. The results showed that total energy input for corn silage (52.1 GJ ha^{-1}) is greater than other systems. The results also revealed that yield and output energy of crops were not significantly affected by field size, whereas energy use efficiency of systems increased significantly as field size increased. Study shows that the cultivation of paddy emits the highest CO_2 eq. emission (6094 kg CO_2 eq. ha^{-1}) among crops, in which around 60% is contributed by methane (CH_4). The efficient use of fertilizers, optimized pumping facilities for irrigation, stopping of crop residue burning in the field and use them for energy supply could be among the options to improve energy use efficiency and mitigate GHG emissions.

Contents

1. Introduction

Energy is one of the principal requirements for the economic growth and social development of a country or region. Scientific forecasts and analysis of energy consumption will be of great importance for the planning of energy strategies and policies [1]. The enhancement of energy efficiency not only helps in improving competitiveness through cost reduction but also results in minimized greenhouse gas (GHG) emissions and environmental

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impacts [2]. About 14% of the global net CO_2 emissions originating the agricultural systems [3], but this share in Iranian agriculture is smaller and estimated to be ~4% [4]. Emissions from this sector in Iran, however, shows an increasing trend during the last two decades due to a high application of synthetic nitrogen, direct energy inputs and intensive use of farm machinery [5].

In Iran, in recent years, the energy efficiency of the agricultural sector has been questioned because of increasing of energy use and the costs due to more mechanized agricultural production [5]. As energy costs rise and fossil fuel reserves decline, energy use efficiency of agricultural systems becomes increasingly important. Many factors contribute to energy productivity but the size of the farm can play major role in adding to its productivity, especially in developing countries like Iran, where the average farm size is relatively small and the majority of farmers own less than five hectare of farm land [6].

The relationship between farm size and energy productivity can be differed per regions by rapid mechanization. The level of mechanization, amount of arable land and type of crop are the important factors that energy use in the agriculture sector depends on them [7]. On the other hand, the amount of energy resources are different in each farming region and on the field, there is a competition among crops into consumption of large energy inputs such as machinery, fertilizers, and irrigation. Studies comparing crop production systems have examined relationship between energy indices and farm size which is reported the different findings. Mandal et al. [8] analyzed the cropping systems in terms of energy use and the economics in different categories of farm size. They concluded that the energy productivity decreases towards larger size of farms, except for pigeon pea mono cropping, where the trend is reverse. A survey in Turkey was performed on energy consumption patterns in different sizes of farms for canola production. According to the results of this study the energy productivity increases with farm size [9].

In the literature there are several techniques for agricultural systems analysis in the view of energy, economic and environmental dimensions. Soni et al. [10] considered the energy use index and CO_2 emissions in rainfed agricultural production systems of Northeast Thailand. In this study, system efficiency, total energy input and corresponding CO_2 eq. emissions were estimated and compared for different crops. In another study by Koga and Tajima [11] energy efficiency and GHG emissions under bioethanol-oriented paddy rice production in northern Japan was investigated. They concluded that there are opportunities for further improvement in energy efficiency and reductions in GHG emissions under whole rice plant-based bioethanol production systems. In other works, the parametric and non-parametric approaches have been used to analyze the efficiency of farmers in agricultural productions [12]. Data Envelopment Analysis (DEA) is a non-parametric model based frontier estimation technique for measuring the relative efficiencies of a homogenous set of Decision Making Units (DMUs) having multiple inputs and outputs [13]. Recently, DEA method has been utilized to estimate the economic and energy efficiency of agricultural products [14,15]. For the environmental costs of food production, Life Cycle Assessment (LCA) is one of the best methodologies for the GHG emissions of agri-food systems, by recognizing energy and inputs used as well as direct and indirect GHG emissions [16]. Pergola et al. [17] reported that he combined use of LCA and energy analysis could be useful to provide information for policy makers and producers in choosing sustainable management systems or products. The joint application of LCA and DEA has also proven to be a suitable method for quantifying operational and environmental targets. Mohammadi et al. [18] applied LCA+DEA methodologies for a total of 94 soybean farms in Iran to benchmark the level of operational input efficiency of each farmer. They concluded that 46% of the farms studied operated efficient and greenhouse gas (GHG) emissions can be mitigated ~11% if inefficient farms turn efficient.

In this regard, there are several studies on energy analysis in production of single crops and fruits like potato [19], wheat [20], canola [12] and tangerine [21], for Iranian agriculture, whereas there is no study on analysis of farming systems from both energy and environmental points of view. The purpose of this study is to examine and compare energy use efficiency and GHG emissions of six crops across size land holdings. Energy analysis in the crop production systems enables to identify the effective farming system in different farm size with respect to energy parameters.

2. Materials and methods

2.1. Site description and data collection

The study was carried out in Golestan province located in North of Iran. The climate is Mediterranean. In the last decade, the mean annual rainfall and mean annual air temperature were 442 mm and 18 °C, respectively. The soil is silt loam derived from alluvial plains and classified as *Typic Xerorthents* based on USDA soil taxonomy, with pH of 7.1–7.9 [22]

The data used in the study were obtained using a face-to-face interview method. A questionnaire form was designed to collect the required information related to various inputs use (electricity, biocides, fertilizer, etc.), the possessed lands by the farmers, their cropping pattern, crops yield, operations time, economical information, etc. The structure of this questionnaire form is similar with ones that had been applied for previous studies [12,19,23]. The selection of producers was based on the cropping patterns and that the farmers should be representative of the selected crops. In addition, secondary data was obtained from similar studies and statistics by various individuals and organizations related to this subject like Agricultural Ministry of Iran. Finally data of 72 farmers were used for computation of energy consumption and its various ratios in crop production systems. These systems were compared in relation to the energy balance with different size land holdings: small (< 2 ha), medium (2–5 ha) and large (> 5 ha) systems for two cycles of six crop rotation that included wheat (*Triticumaestivum*), barley (*Hordeumvulgare* L.), canola (*Brassica napus* L.), soybean (*Glycine max* (*L.*) *Merrill*), corn silage (*Zea mays*) and paddy (*Oryza sativa* Linnaeus). These are the major crops grown in this region and all of them are cultivated under irrigated farming. Two growing cycles are possible. From the month of December up to mid-June they plant wheat, barley and canola; and from July up to November they cultivate soybean, corn silage and paddy. Depending on the field size, the farmers may plant one to three crops per cycle.

2.2. Energy and CO_2 emission analyses

The energy efficiency of the agricultural system was evaluated by the energy ratio between output and inputs. The flow diagram illustrating the energy inputs, GHG emissions and products including main products and residues during crop cultivation and transportation

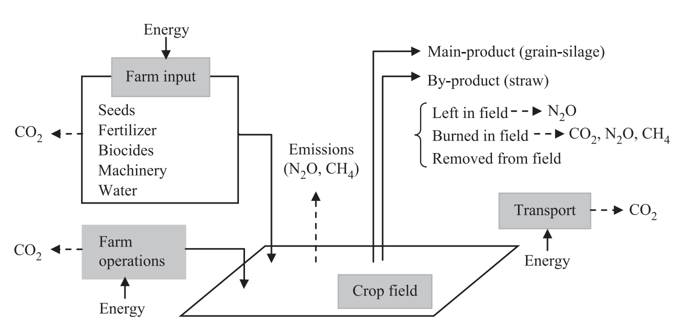

Fig. 1. The diagram of the energy inputs, greenhouse gas emissions and products during crop cultivation.

steps is given in Fig. 1. Human labor, machinery, electricity, diesel fuel, fertilizers, biocides and seed amounts and output yield values have been used to estimate the energy ratio. The physical quantities of inputs used were converted into energy values using the most recent energy coefficients taken from the literature and adjusted for manufacturing technology improvements. The energy equivalents used are shown in Table 1. The energy equivalent of an input is the energy required for production and transfer from primary production to the end user. The energy costs of labor were estimated by taking into consideration the labor requirements of each practice. Its energy equivalent indicates the muscle power used in farm operations. Biocides and fertilizers energy equivalents include the energy inputs required for production, formulation, packaging and transportation. The energy sequestered in electricity and diesel fuel shows their heating value and the energy needed to make their energy available directly to the farmers. The total energy associated with tractors and farm machinery consists of the energy for production, repairs and maintenance and delivering to the farm. Energy related to machinery input was reported in terms of MJ kg^{-1}. The weight of machinery depreciated per hectare of crops production during the production period was calculated as follows [12]:

$$TW = (G \times W_h)/T \quad (1)$$

where TW (kg ha^{-1}) is the depreciated machinery weight, G (kg) is the total machinery weight, W_h (h ha^{-1}) is the time of machinery use per unit area and T (h) is the economic life time of machinery.

Total physical output includes to both the economic and by-product yield (straw). The energy output from the grain and by-product yield was also estimated except for corn silage where only the economic yield was calculated. Outputs were converted into energy unit using their corresponding coefficients (Table 1). The input energy was divided into renewable and non-renewable forms, and also direct and indirect forms. Non-renewable energy includes machinery, diesel fuel, electricity, chemical fertilizers and chemicals, and renewable energy consists of human labor, farm-yard manure (FYM) and seed. Direct energy covers human labor, diesel fuel, and electricity; while indirect energy comprises energy embodied in chemical fertilizers, FYM, biocides, seeds and machinery. Based on the energy equivalents of the inputs and outputs, the energy use efficiency and net energy value were calculated. The net energy value was obtained by subtracting the energy output from the total energy inputs. The energy use efficiency was calculated by dividing energy output by total energy inputs (Table 2).

In the current study, the amount of GHG emissions that can be produced by inputs in crops cultivation were estimated by using CO_2 emission coefficient of farm inputs in the literature. Three key GHGs emissions under consideration are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). The values of the direct and indirect N_2O emissions and the CO_2 emissions related to inputs used were estimated using published references and the IPCC [3] guidelines. The amount of produced CO_2 equivalent was calculated by multiplying the input used rate (diesel fuel, chemical fertilizer, biocide, farm yard manure and electricity) by their corresponding emission coefficient that is shown in Table 3. N_2O is emitted directly from agricultural farms, as well as from N that leaves the field and enters other ecosystems via volatilization and leaching. For the reference case, we assume that this includes emissions directly from the field, and indirect emissions from N leached or volatilized from the fields. The CH_4 emissions caused by burning crop residues in the farms and generated from paddy fields were also computed according to IPCC [3].

Table 1
Energy equivalent of inputs and outputs in agricultural production.

Inputs	Unit	Energy equivalent (MJ $unit^{-1}$)	Reference
1. Human labor	h	1.96	[5]
2. Machinery	kg	108[a]	[24]
3. Diesel fuel	L	47.3	[5]
4. Chemical fertilizers			
(a) Nitrogen	kg	59	[25]
(b) Phosphate (P_2O_5)	kg	17	[25]
(c) Potassium (K_2O)	kg	10	[25]
5. Farmyard manure	kg	0.30	[5]
6. Biocides			
(a) Insecticides	kg	58	[5]
(b) Fungicides	kg	115	[5]
(c)Herbicides	kg	295	[5]
7. Electricity	kWh	11.93	[26]
8. Seed	As output of crop production system		
Output			
1. Cereal	kg	14.7	[5]
2. Soybean	kg	23.8	[2]
3. Canola	kg	27.3	[27]
4.Corn silage	kg	4.14[b]	[28]
5.Strawcereal	kg	12.5	[26]
6.Straw soybean	kg	18.29	[2]
7.Straw canola	kg	17.25	[2]

[a] Includes energy required for manufacture and maintenance, see Eq. (1).
[b] The energy equivalent of corn silage was considered in 32% dry matter.

3. Results and discussion

3.1. Management practices and energy input

Main practices and average rate of inputs applied in the crops are illustrated in Table 4. Tillage operations were performed using a moldboard ploughing at a depth of 25–30 cm, disc harrowing (depth of 15 cm), chisel ploughing (depth of 20–25 cm) and bund former (for paddy). Chemical fertilizers and farmyard manure (FYM) are applied among the surveyed farms and distributed

Table 2
Definition of energy parameters.

Parameter	Definition	Unit
Renewable energy (E_r)	Human labor + FYM + seed	GJ ha^{-1}
Non-renewable energy (E_n)	Machinery + diesel fuel + electricity + chemical fertilizers + biocides	GJ ha^{-1}
Direct energy (E_d)	Human labor + diesel fuel + electricity	GJ ha^{-1}
Indirect energy (E_i)	Machinery + chemical fertilizers + biocides + FYM + seed	GJ ha^{-1}
Total energy inputs (E_T)	$E_T = E_r + E_n / E_T = E_d + E_{ind}$	GJ ha^{-1}
Energy output (E_O)	Energy in the harvested yield	GJ ha^{-1}
Energy use efficiency	E_O/E_T	–
Net energy value (NE)	E_O-E_T	GJ ha^{-1}

Table 3
Greenhouse gas (GHG) emission coefficients of agricultural inputs.

Inputs	Unit	GHG coefficients (kg CO_2 eq. unit^{-1})	Reference
Off-farm emissions (emissions embodied in inputs)			
Chemical fertilizers	kg		
(a) Nitrogen		1.3	[10,29]
(b) Phosphate (P_2O_5)		0.2	[10,29]
(c) Potassium (K_2O)		0.15	[10,29]
Biocides	kg		
(a) Insecticides		6.3	[10,29]
(b) Fungicides		5.1	[10,29]
(c) Herbicides		3.9	[10,29]
Diesel for farm traction and transportation	L	0.016 kg CO_2eq./MJ diesel × 36.4 MJ/L diesel	[30]
On-farm emissions			
Fertilizer N	kg	4.7 (0.01 kg N_2O-N/kg N)	[3,29]
Diesel for farm traction and transportation	L	0.074 kg CO_2eq./MJ diesel × 36.4 MJ/L diesel	[30]
Farmyard manure	tone	0.005	[31]
Residue burned	kg	0.037	estimated from [3]
N in residues returned to soil	kg	4.7 (0.01 kg N_2O-N/kg N)	[3,30]
Irrigation (CH_4 gas for paddy case)	Day	1.1 kg CH_4/ha/day × 25 kg CO_2eq.	estimated from [3]
Electricity credit	kWh	0.8	[30,32]

Table 4
Main field operations and average rate of inputs applied in the farming systems analyzed per hectare.

Practice	Wheat	Barley	Canola	Soybean	Corn silage	Paddy
Main tillage	Mouldboard plough+Disc harrow	Mouldboard plough+Disc harrow	Disc harrow+Chisel plough	Disc harrow+Chisel plough	Mouldboard Plough+Disc harrow	Disc harrow+Bund former
Fertilizer rate (chemical kg - manure t)	126N 79 P_2O_5 31 K_2O 4.2 FYM	116 N 72 P_2O_5 39 K_2O 4.5 FYM	134 N 61 P_2O_5 14 K_2O 1.8 FYM	83 N 46 P_2O_5 12 K_2O 4.7 FYM	192 N 120 P_2O_5 67 K_2O 5.8 FYM	207 N 52 P_2O_5 59 K_2O 0 FYM
Seeding rate (kg)	210	216	7	68	27	81
Pest control -biocides (kg)	3.2	2.7	2.4	5.2	4.3	14.8
Irrigation Electricity (kWh)	209	190	154	1125	1903	1216
Residue management	Incorporation- Removing	Incorporation- Removing	Incorporation – Burning- Removing	Incorporation – Burning- Removing	Incorporation	Removing

using fertilizer and manure spreader. In paddy farming, only chemical fertilizer was utilized. It was observed that spraying biocides was high for paddy, and hoeing was a very common practice for soybean, canola and corn silage using cultivator plough. As it is seen from Table 4, the corn silage required the highest electricity for pumping water with average of 1903 kWh ha^{-1}. For paddy, corn silage and soybean, some farms in the region are irrigated by irrigation channel and other operators use pumps to bring water to their farms, whereas in wheat, barley and canola farming, water for irrigation is supplied only from groundwater resources.

In recent years, farmers were encouraged to return the harvested crop residues to the land to protect the soil from erosion and maintain soil organic matter. The residue management was performed by using a straw chopper or rotary harrow after harvesting. However in canola and soybean, some farmers didn't carry out incorporation and prefer to burn the crop residue.

Total energy input for the studied crops is presented in Table 5. Energy input for corn silage (52.1 GJ ha^{-1}) is highest followed by paddy (45.5 GJ ha^{-1}), soybean (31.7 GJ ha^{-1}), wheat (26.2 GJ ha^{-1}), barley (25.0 GJ ha^{-1}) and canola (19.7 GJ ha^{-1}).

Further, the total energy use, though the magnitudes vary in different crop production systems, gradually decrease with the increase in size of land holdings in every farming system, i.e., the lowest total energy is used by small farms and the highest by large farms. In canola systems, trend was found reverse that total energy input is the lowest in medium land holdings. For wheat, barley, canola and paddy, energy used in the fertilization represented the major share namely between 36% and 54% of the total energy input. Energy usage in fertilization operation includes both direct and indirect energy consumption for the production of nitrogen fertilizer at the factory, transportation to the farm and applying it at the farm.

In corn silage, the most energy consuming practice was irrigation with share of 43% of total energy input. Also, the irrigation was the largest energy operation in soybean and second main operation in paddy. The high contributions of irrigated energy can be interpreted by applying the flood irrigation method, lack of good leveling of farmland low efficiency of water pumping systems leaded to the excessive use of water and energy in the form of electricity.

The use of nitrogen, phosphorus and potassium fertilizer is the most in corn silage systems as it required a mean value of 17.6 GJ ha^{-1}. Soybean needed the least energy for fertilization (8.2 GJ ha^{-1}). Soybean is an annual legume crop which can save more energy due to biologically nitrogen fixation in soil reflecting the lower N fertilizer requirements compared to cereal crops [27]. Also, the inclusion of soybean in the wheat, barley and canola rotation could be the reason that the fertilizer energy use was lower in the above crops compared to the corn silage and paddy. Our data is confirmed by the results reported by Hoeppner et al. [33] that showed lower total energy requirements for rotations that included grain legume or perennial forage legume crops.

The amount of energy use for plant protection by biocides is the largest in paddy (4.8 GJ ha^{-1}). For other systems it varied from

Table 5
Energy input (reported as GJ ha^{-1} year^{-1}) required for each crop in various agricultural activities in small (< 2 ha), medium (2–5 ha) and large (> 5 ha) farms.

Crop	Field size	Field operations							
		Soil tillage	Sowing	Fertilization	Plant protection	Irrigation	Harvesting	Residue management	Total
Wheat	Small	4.8	3.8	12.1	1.7	2.8	1.7	0.8	27.5
	Medium	4.5	3.6	11.7	1.5	2.4	1.5	0.7	25.9
	Large	4.4	3.5	11.5	1.6	2.4	1.5	0.7	25.4
Barley	Small	4.7	3.7	11.6	1.5	2.7	1.6	0.7	26.4
	Medium	4.3	3.6	11.1	1.4	2.2	1.5	0.7	24.7
	Large	4.2	3.6	10.9	1.4	2.0	1.4	0.6	24.1
Canola	Small	2.8	0.9	10.7	1.1	2.1	1.9	1.2	20.7
	Medium	2.3	0.9	10.6	1.0	1.8	1.7	1.1	19.4
	Large	2.1	0.8	10.7	1.1	1.7	1.6	1.1	19.0
Soybean	Small	3.1	2.2	8.4	1.8	13.9	2.7	0.8	32.9
	Medium	2.8	2.1	8.1	1.6	13.5	2.4	0.8	31.3
	Large	2.6	2.1	8.2	1.7	13.3	2.2	0.7	30.8
Corn silage	Small	4.5	1.1	17.8	1.5	23.6	3.8	1.5	53.8
	Medium	4.2	1.1	17.4	1.5	22.8	3.4	1.3	51.7
	Large	4.1	1.0	17.5	1.4	22.3	3.2	1.3	50.8
Paddy	Small	3.7	2.5	16.6	4.9	15.3	3.5	0.7	47.2
	Medium	3.4	2.3	16.3	4.9	14.5	3.1	0.8	45.3
	Large	3.4	2.2	16.1	4.6	14.1	2.8	0.7	43.9

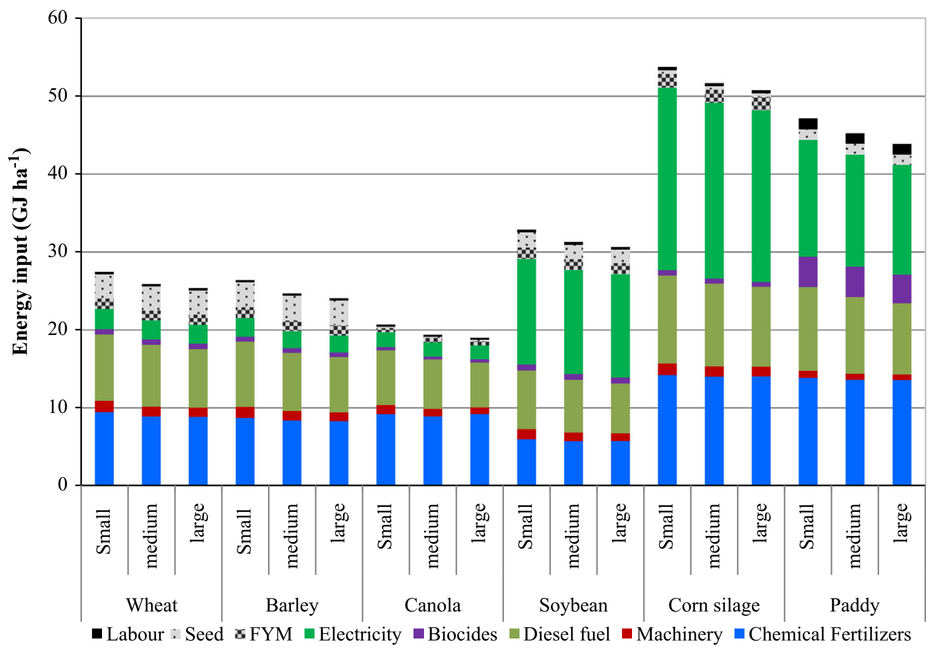

Fig. 2. The share of different inputs from total energy input in crops production for the three farming systems analyzed: small (< 2 ha), medium (2–5 ha) and large (> 5 ha) system.

1.1 GJ ha^{-1} for canola to 1.7 GJ ha^{-1} for soybean. In the research area, where paddy growth is affected by problems such as pests and diseases, a crop management determined by high biocides input level can indicate the best option to keep down output losses. In a study carried out in Turkey, the fertilizer has the biggest share in silage corn production with the changing rate of 61.94% for ridge tillage method and 68.86% for no-tillage method [28].

Mechanization and diesel fuel mainly concerned soil tillage, sowing and crop harvest. Comparing the size of land holdings, the energy requirements for tillage decreases towards higher size of farms, except for paddy where in medium and large categories are equal (Table 4). It is evident that, wheat used the greatest energy for soil tillage among other crops with 4.5 GJ ha^{-1} followed by barley and corn silage. It reveals that farmers having smaller size of land holdings use more energy for soil tillage, sowing and harvesting. Due to the increasing horsepower of the tractors and width of farm machinery on larger farms, the farmers carried out the field operations in less time as compared to smaller farmers. The increased cost of labor use compared to mechanical power has encouraged the farmers to utilize wider and stronger agricultural machinery, especially on larger systems for farm operations. In a study carried out in India, Singh reported that manual labor use is negatively correlated with mechanization index [34]. Unakitan et al. [9] showed that the farm machinery and labor application decreases while farm size increases for canola production. Our results showed that the total energy input per area unit in small fields was 7% higher than that of large fields.

The share of inputs from total energy input for each crop is shown in Fig. 2. For all crops, energy included in the diesel fuel represented a high share namely between 21% and 34% of the total input. For the study area, fuel is exclusively used for machinery operations and irrigation. Fuel consumption per hectare declined with increasing farm size. The energy consumed by machinery varied from 0.8 GJ ha^{-1} in paddy to 1.4 GJ ha^{-1} in corn silage (Fig. 2). Energy included in the seeds for sowing crops had a negligible share in the total energy input

Table 6
Mean value of the renewable (E_r), non-renewable (E_n), direct (E_d) and indirect (E_i) energy forms, crop yield and by-product yield for each crop in the three farming systems analyzed: small (< 2 ha), medium (2–5 ha) and large (> 5 ha) system.

Crop	Field size	E_r (GJ ha^{-1})	E_n (GJ ha^{-1})	E_d (GJ ha^{-1})	E_i (GJ ha^{-1})	Yield (t ha^{-1})	By-product (t ha^{-1})
Wheat	Small	4.7	22.7	16.0	11.4	3.4	3.9
	Medium	4.6	21.2	15.2	10.7	3.6	4.2
	Large	4.7	20.7	15.1	10.2	3.7	4.2
	Mean	4.7	21.5	15.4	10.8	3.6	4.1
Barley	Small	4.9	21.5	15.3	11.1	3.6	4.1
	Medium	4.8	19.9	14.7	10.0	3.9	4.3
	Large	4.8	19.3	14.5	9.5	4.1	4.4
	Mean	4.8	20.2	14.9	10.2	3.9	4.3
Canola	Small	1.0	19.7	11.5	9.2	2.6	3.2
	Medium	1.0	18.4	11.0	8.4	2.7	3.4
	Large	1.0	18.0	11.2	7.8	2.9	3.6
	Mean	1.0	18.7	11.2	8.5	2.7	3.4
Soybean	Small	3.8	29.1	11.4	21.5	3.0	3.6
	Medium	3.6	27.7	10.8	20.5	3.3	3.8
	Large	3.6	27.2	10.8	20.0	3.4	3.9
	Mean	3.6	28.0	11.0	20.7	3.2	3.8
Corn silage	Small	2.6	51.1	18.6	35.2	31.6	–
	Medium	2.5	49.2	18.1	33.6	34.1	–
	Large	2.5	48.2	18.0	32.7	35.2	–
	Mean	2.6	49.5	18.2	33.8	33.6	–
Paddy	Small	2.8	44.4	20.0	27.2	5.4	6.8
	Medium	2.7	42.6	19.6	25.6	5.7	7.1
	Large	2.7	41.2	19.3	24.6	5.7	7.2
	Mean	2.7	42.7	19.6	25.8	5.6	7.0

Table 7
Summary of energy parameters results with (+R) or without (-R) including the biomass residues in output for each crop in the three farming systems analyzed: small (< 2 ha), medium (2–5 ha) and large (> 5 ha) systems.

Crop	Field size	Output energy (GJ ha^{-1})		Net energy(GJ ha^{-1})		Energy use efficiency		
		(-R)	(+R)	(-R)	(+R)	(-R)	(+R)	
Wheat	Small	50.0	98.7	22.5	71.2	1.8	3.6	a[a]
	Medium	52.9	105.4	27.0	79.6	2.0	4.1	b
	Large	54.4	106.9	29.0	81.5	2.1	4.2	b
	Mean	52.4	103.7	26.2	77.4	2.0	4.0	–
Barley	Small	52.9	104.2	26.5	77.8	2.0	4.0	a
	Medium	57.3	111.0	32.6	86.4	2.3	4.5	b
	Large	60.3	115.3	36.2	91.2	2.5	4.8	c
	Mean	56.8	110.2	31.8	85.1	2.3	4.4	–
Canola	Small	71.8	127.0	51.1	106.3	3.5	6.1	a
	Medium	74.5	133.2	55.1	113.8	3.8	6.9	b
	Large	80.0	142.1	61.0	123.0	4.2	7.4	c
	Mean	75.4	134.1	55.7	114.4	3.8	6.8	–
Soybean	Small	71.4	137.2	38.5	104.3	2.2	4.2	a
	Medium	78.5	148.0	47.2	116.7	2.5	4.7	b
	Large	80.9	152.3	50.1	121.5	2.6	4.9	c
	Mean	77.0	145.8	45.3	114.8	2.4	4.6	–
Corn silage	Small	130.8	–	77.0	–	2.4	–	a
	Medium	141.2	–	89.5	–	2.7	–	b
	Large	145.7	–	94.9	–	2.9	–	c
	Mean	139.2	–	87.1	–	2.7	–	–
Paddy	Small	79.4	164.4	32.2	117.2	1.7	3.5	a
	Medium	83.8	172.5	38.5	127.2	1.8	3.8	b
	Large	83.8	173.8	39.9	129.9	1.9	4.0	c
	Mean	82.3	170.2	36.8	124.8	1.8	3.8	–

[a] Within the same row, the values followed by a different letter differ at $P \le 0.05$ by Duncan's test.

for canola and corn silage, less than 1%. The human labor had a low share within the energy balance and its usage decreases while field size increases. The highest and lowest labor use was recorded for paddy (3%) and corn silage (0.8%), respectively. In India, the maximum energy use of human labor (~1.9 GJ ha^{-1}) was observed for rice cultivation in the cropping systems [35]. When comparing labor against the other input sources, human labor in wheat, barley and soybean finds the smallest share with amount of 0.30 GJ ha^{-1}, 0.28 GJ ha^{-1} and 0.36 GJ ha^{-1}, respectively. This is in agreement with the literature for different crops [20,28]. In some studies the energy from human labor was not assessed since it had a small contribution in the total energy input [2].

The distribution of energy inputs in production systems according to the renewable, non-renewable, direct and indirect energy forms was also investigated and the outcomes are shown in Table 6. The results present that there is a significant difference between renewable and non-renewable energy sources for all of the studied systems. The findings imply that, share of non-renewable energy for canola production is much greater than that of other systems; this is caused mainly by the high share of fertilization from total energy input in its farming. Our results on canola are in agreement with the results of other authors [9,12] that showed a range 95–99% of energy input comes from non-renewable energy. It indicates that, farmers having larger size of land holdings use less non-renewable energy inputs per hectare. Regarding the direct and indirect energy, it is worth mention that the ratio of indirect energy is higher than direct energy for each crop in all systems, but by increasing the size of farms, indirect energy use gradually decreases and the percent direct energy use increases. Pishgar Komleh et al. [36] reported the similar trend from reduction of non-renewable energy and indirect energy while the farm size increases in corn silage production.

3.2. Energy output

The physical output per hectare (grain yield and straw) ranged with the crop production systems and size of land holding (Table 6). The variation in yield can depend on the intrinsic potential of the crops in the sequence and differential input-use behavior. In corn silage the total physical yields were significantly affected by increasing plot size from small to medium and large (31.6 vs. 34.1 and 35.2 t ha^{-1}). The slight differences in other crops may be due to a peculiar interaction between weather conditions and crop growth in the region. The energy output was calculated based on the entire biomass produced by the crops. Inclusion of residue biomass as part of the output energy has a large effect on the final balance. When no energy coming from the residues is considered, corn silage ranked the highest in terms of energy output followed by paddy with 82.3 GJ ha^{-1}. The addition of residual biomass in the energy balance introduced important changes in the output energy, exception made for corn silage. With including residues, the mean values of energy outputs, in GJ ha^{-1} unit, were calculated as 170.2, 145.8, 139.2, 134.1, 110.2 and 103.7 for paddy, soybean, corn silage, canola, barley and wheat, respectively (Table 7). Results also present that the yield (both grain and straw) and obviously the energy output is increased with the increase in size of farm, i.e., from small to large category, showing that large farms have greater level of productivity compared to small farms. Our results are supported by Mandal et al. [8] that showed a direct relationship between yield and farm size that consequently affects the energy output. Also, Unakitan et al. [9] concluded that in canola production, large farms have a lower energy input average (17.6 GJ ha^{-1}) but a higher energy output average (92.0 GJ ha^{-1}) compared to small and medium farms.

3.3. Energy use efficiency

Table 7 presents the values of energy balance for crop production in the three field sizes, along with average values for energy output (GJ ha^{-1}), net energy (GJ ha^{-1}) and energy use efficiency considering both output energy scenarios, with or without the energy of the residual postharvest biomass. With no residues included in the output, corn silage with a value of 87.1 GJ ha^{-1} and canola with average of 3.8 were the crops with the highest net

Table 8
Amount of the GHG emissions for each crop (reported as kg CO_2eq. ha^{-1}) in north Iran.

Inputs	Wheat	Barley	Canola	Soybean	Corn silage	Paddy
Off-farm emissions (emissions embodied in inputs)						
Chemical fertilizers						
(a) Nitrogen	75.1	69.4	80.3	49.7	115.1	123.8
(b) Phosphate (P_2O_5)	15.7	14.5	12.3	9.3	24.1	10.3
(c) Potassium (K_2O)	4.6	5.9	2.2	1.9	10.1	8.9
Biocides						
(a) Insecticides	3.4	2.9	8.7	15.0	11.8	6.1
(b) Fungicides	3.9	2.6	0.0	5.6	5.1	9.4
(c) Herbicides	7.4	6.9	4.2	6.5	5.5	46.9
Diesel for farm traction and transportation	98.4	94.2	78.5	84.9	132.1	122.1
On-farm emissions						
Fertilizer N	271.7	250.9	290.4	179.8	416.0	626.3
Diesel for farm traction and transportation	455.2	435.5	363.2	392.8	611.0	564.8
Farmyard manure	21.7	22.5	8.8	23.5	29.2	0.0
Residue burned	0.0	0.0	78.0	101.2	0.0	0.0
N in residues returned to soil	46.2	48.5	13.4	21.4	0.0	0.0
Irrigation (CH_4 gas for paddy case)	0	0	0	0	0	3602.5
Electricity credit	167.7	152.0	123.5	899.7	1522.4	973.1
Total	1171.1	1105.7	1063.5	1791.4	2882.2	6094.1

energy and energy use efficiency, respectively. Also, lowest net energy and energy use efficiency were found for wheat (26.2 GJ ha^{-1}) and paddy (1.8). Different results were found when the energy of the residues was included to estimate the energy performance. The energy indices of all crops, except corn silage (without by-product), were enhanced greatly.

The highest net energy increments were observed for paddy and wheat. The paddy obtained the first place for net energy with average of 124.8 GJ ha^{-1} followed by soybean with 114.8 GJ ha^{-1}, canola with 114.4 GJ ha^{-1}, barley with 85.1 GJ ha^{-1} and wheat with 77.4 GJ ha^{-1}. Paddy after corn silage required the most energy input among studied systems, whereas because of high yield, the biggest amount of net energy was found for this crop. Overall, net energy averaged about 47 and 103 GJ ha^{-1} with or without including the biomass residues in output that its value increases with increase in plot size for all of crops. Relative to large fields were 10% and 6% more efficient while small one was 12% and 8% less efficient with or without the energy of the residue, respectively (data not shown).

In case of energy use efficiency, the canola found the highest value (6.8) and for other systems it varied from 3.8 in paddy to 4.6 in soybean systems. The above ground biomass of paddy increased the energy use efficiency to 111% and it was lowest for canola that energy use efficiency increased by 79%. Bojaca and Schrevens [37] reported that the energy parameters were improved dramatically when the energy of the residues was included in the output of vegetables cropping systems. The energy flow analysis in the farming systems highlights the role that residue biomass plays in the energy balance especially for paddy and wheat crops in the research area. The agricultural residues are a major potential feedstock for energy source that frequently mentioned [38,39].

In particular, the energy ratio that we estimated for wheat, soybean and rice paddy agreed closely with the values that Mandal et al. [8], Sartori el al. [40] and Chaudhary et al. [35] obtained. Comparing the size of fields, implying large farmers maintain considerably greater level of the energy use efficiency. In the other words, the energy use efficiency was significantly higher in the large size of farms in comparison to small systems for every crop. The main reason for this is the increasing field size increases productivity while decreasing total energy input for production units due to low inputs of larger farms. These results are in agreement with Pishgar Komleh et al. [36] that showed the increase in farm size leads to increase in the net energy and

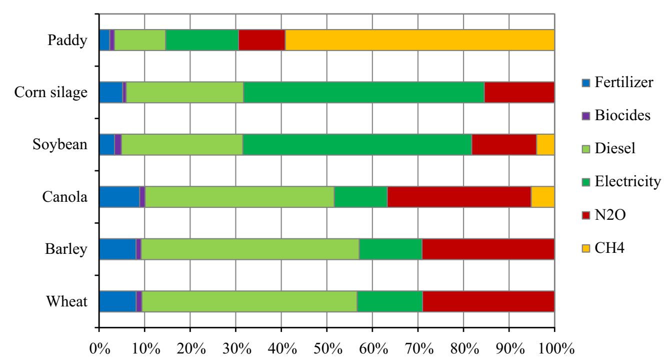

Fig. 3. Contribution of different subsystems in the GHG emissions for 1 ha crops production.

energy use efficiency for corn silage production in Iran. Tipi et al. [41] reported that the average energy use efficiency for wheat production is 3.09, and this value increases with farm size.

3.4. GHG emissions

The data collected for this study were converted into kg CO_2eq. using emission coefficients. The results of GHG emissions of surveyed crops are presented in Table 8. GHG emission is the highest in paddy (6094 kg CO_2 eq. ha^{-1}) and for other crops it ranged from 1064 kg CO_2 eq. ha^{-1} in canola to 2882 kg CO_2 eq. ha^{-1} in corn silage. A contribution analysis has also been carried out with reference to the considered crops and presented in Fig. 3. This figure can be helpful to assess the role of the different subsystems that contribute to the global warming impact of crops production. For wheat, barley and canola crops, diesel fuel and N_2O are among the most important sources of CO_2 emissions; while in soybean and corn silage the main CO_2 emission resources were electricity and diesel fuel, respectively. It was due to higher irrigation water consumption in soybean and corn silage compared to wheat, barley and canola crops resulting in higher electricity usage and CO_2 emissions. In paddy production the share of CH_4 was the highest (around 60%) followed by electricity. As it is seen from Fig. 3, the share of electricity input in CO_2 emissions is about 12% in canola to 53% in corn silage. For diesel it changes from 11% for paddy to 48% for barley. Diesel fuel is involved with all operations mainly tillage and harvesting that affects emission directly. The fuel consumes for water pumping, in addition to

electricity, in some farms for soybean, corn silage and paddy cultivation. The data in Table 8 show that, the average amount of CO_2 emission from electricity, diesel fuel was the biggest for wheat, barley and canola. The application of fossil energy use has been reported as the main contributors to the GHG emissions [42,43]. Since in the literature there is no study on the environmental effects of Iranian farming, and very little attention has been paid to the GHG emissions from the agricultural sector, we compared our results with earlier works in other Asian countries such as China, Thailand and Japan. Hokazono and Hayashi [44] investigated the environmental impacts of rice production systems in Japan. They reported that, the direct field emissions (mainly CH_4) contributed about 75% of total global warming potential in conventional systems. Knudsen et al. [45] reported that total CO_2 eq. emissions for 1 t of soybean produced under conventional system in China was 263 kg, from which about 20% derived from crop residue burning; they further recommended that stopping the burning of crop residues in the field would improve the environmental profile of the conventional soybean production system. Soni et al. [10] investigated GHG emissions in some agricultural production systems in Northeast Thailand. They reported that total CO_2 eq. emissions for various crop productions varied from 137 kg to 1112 kg CO_2eq. for pond culture and transplant rice, respectively.

Moreover, residue management could be another factor that influences GHG emissions. In most of the farms in the region, a part of the crop residues is burned in the field, most? farmers leave the crop residues in the field or harvest and remove it from the field for the livestock fodder. Biomass burning has been identified as an important source of emissions in agricultural environment especially for the developing countries like Iran; however, it continues to be associated with large information gaps and uncertainties [46]. CO_2 equivalent emissions derived from residue burning also depend on the price of straw [47]. Low price of straw is one of the reasons that farmers are not motivated to remove residues from the field and they burn them resulting in higher GHG emissions. However the higher price of straw can encourage the farmers to collect crop residues. The crop residue also can be used as a source of bioenergy. Our finding showed that energy in crop residues is bigger than total energy input and close to the yield energy. This great potential could be considered for utilization of modern technologies on biomass energy conversion of agricultural residues in the region. Considerable efforts have been carried out to obtain the different utilizations for by-products such as electricity generation [48] and bioenergy production [49].

3.5. Options to improve energy use efficiency and GHG performance

GHGs balance and LCA methodology in the field of agricultural production are still in its infancy in Iran. It would be in the interest to the economy of the country to promote the use of such techniques for the assessment of potential environmental impacts to meet the growing demand for answers to questions regarding the sustainability of agricultural systems. The results that we obtained in this study provide some important insights for future plans regarding energy consumption and GHG emissions in the region. Indices used to assess the energy efficiency of different local farming systems showed a positive balance between the economic output and the energy embodied on input sources (energy use efficiency values were all bigger than 1.0) (Table 7). But these sources are usually utilized inefficiently and energy savings could be obtained without significant yield reduction. Adoption of integrated farming techniques may be a viable solution to improve the energy use efficiency of crops compared to conventional management. In our study, fertilization is among most important inputs for which increased yield could be fundamental to reduce energy inputs. Due to high energy requirements for mineral fertilizers production, the improved fertilizer use efficiency by adjusting nutrient supply to the actual crop nutrient requirements is a crucial step to attaining high energy efficiency [50].

Non-renewable energy sources such as N fertilizer and biocides are also a principal source of CO_2 and N_2O emissions, therefore, increasing performance of non-renewable energy and finding alternatives is important for the GHGs emissions mitigation. Another option for saving energy is involves irrigation. A huge variation was observed in the amount of energy use in irrigation operation for the crops planted in the area. Irrigation is also a very carbon (C)-intensive practice. Follett [51] estimated C emission from pump irrigation at 150–200 kg CE/ha/year depending on the source of energy. Plappally and Lienhard [52] reported that pressure based pumping systems for extracting ground water resources in agriculture have high energy intensity and the energy intensities in irrigation change with the type of crops planted, with area and with an increase in pressure requirements. Similar to fertilizer use, enhancing water use efficiency (WUE) is important for reducing emissions and enhancing energy productivity. In studied environment, WUE is low due to old irrigation systems, and lack of good maintenance and inefficient irrigation methods. Encouraging farmers for using sprinkler irrigation, drip and sub-irrigation, instead of flood and furrow irrigation, for most upland crops (although paddy requires flooding), adopting conservation tillage with residue mulch to reduce evaporation losses, and using supplemental irrigation only at critical stages of crop growth can enhance WUE [53]. Among mechanical operations, tillage for land preparation has great potential for reducing energy inputs. Major farmers applied the conventional tillage for their land preparation, and this is a reason which the tillage operation has a large share from total energy input. Deep tillage requires the use of high powered machines, which is very energy consuming, and is not always justified through a significant increase in yield [54]. Tillage operation is also involve with CO_2 emission due to fossil fuel use by farm machinery and additional emissions associated with production and delivery of fuels to the farm, and the energy consumed in manufacture, transportation, and repair of the machines [43]. Smith et al. [55] reported that changes in tillage practice can lead to sequestration of C in agricultural soils and reduction of CO_2 emissions to the atmosphere. Kern and Johnson [56] estimated that C emissions associated with crop production using conventional tillage, reduced tillage, and no-till were 52.8, 41.0, and 29.0 kg C ha^{-1} per year, respectively. Changing from conventional tillage to minimum tillage or no-till could be estimated to enhance energy use efficiency and decrease CO_2 emissions due to energy-savings on fuel from reduced trips across the field.

To sum it up, population growth and on the other hand global climate changes are putting high pressure on food production systems, resulting in the intensifying the use of water and energy sources and enlarging the environmental footprints. This paper presented a case study of energy analysis and environmental impacts of crop production systems in north of Iran, to better understand the main pathways for reducing the environmental footprints of water and energy use. In addition to options mentioned above, policy makers should also undertake new strategies to boost energy efficiency and ensure more environmental friendly energy use patterns in Iranian agriculture. These strategies can include:

- Providing educational opportunities for producers related to farm management and training them to use various sources of energy in a proper pattern.
- Increasing water productivity and energy use efficiency as the main pathways for reducing the environmental footprints of food production system in the region.

– Adequate financial support for increasing field size that will lead to energy usage effectiveness in these farms (based on this study results).
– Planning governmental policies on researching and introducing new agriculture methods like conservation farming, integrated farming systems and organic farming.

4. Conclusions

The aim of this study was to assess the energy use efficiency and CO_2 emissions of farming systems, located in Golestan province of Iran. Our findings showed that the mean value of energy use efficiency were 6.8, 4.8, 4.4, 4.0, 3.8 and 2.7 for canola, soybean, barley, wheat, paddy and corn silage, respectively. With the inclusion of the residues in the output, the energy balance of crops was considerably improved. The results of investigating land size lead to note that larger farms have higher productivity and use energy more efficient than smaller farms. Our study also showed that agricultural systems in the area depend mainly on inputs of non-renewable energy (75%) associated with fertilization, irrigation and machinery practices. On the other hand, these agricultural operations are C-intensive and enhance CO_2 and other GHG emissions. The outcomes of environmental impact assessment revealed the GHG emissions range from 1064 kg CO_2 eq. ha^{-1} in canola to 6094 kg CO_2 eq. ha^{-1} in paddy. The most sources of GHG emissions for wheat, barley and canola crops were obtained diesel fuel and direct emission of N_2O, for soybean and corn silage, they were electricity and diesel fuel, and in paddy production, CH_4 was found the largest contributor.

The large amount of water in flood irrigation caused to the high energy consumption and CO_2 emissions in paddy cultivation. Hence, raising water use efficiency by adopting mechanized irrigation systems, accurate fertilization management and use of crop residues as energy source can also be employed to decrease rate of non-renewable energy inputs and consequently the GHG emissions. Likewise, proper application of agricultural machinery and equipment, matching the machinery field capacity with farm size, shifting from conventional tillage to conservation tillage methods can reduce fossil fuel consumption and improve the environmental profile of farming systems in the region.

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